

Cortes, Aiza; Rejuso, Arnold Jesfel; Santos, Justine Ace; Blanco, Ariel

Article

Evaluating mitigation strategies for urban heat island in Mandaue City using ENVI-met

Journal of Urban Management

Provided in Cooperation with:

Chinese Association of Urban Management (CAUM), Taipei

Suggested Citation: Cortes, Aiza; Rejuso, Arnold Jesfel; Santos, Justine Ace; Blanco, Ariel (2022) : Evaluating mitigation strategies for urban heat island in Mandaue City using ENVI-met, Journal of Urban Management, ISSN 2226-5856, Elsevier, Amsterdam, Vol. 11, Iss. 1, pp. 97-106,
<https://doi.org/10.1016/j.jum.2022.01.002>

This Version is available at:

<https://hdl.handle.net/10419/271448>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>

HOSTED BY



ELSEVIER

Contents lists available at ScienceDirect

Journal of Urban Management

journal homepage: www.elsevier.com/locate/jum

Research Article

Evaluating mitigation strategies for urban heat island in Mandaue City using ENVI-met

Aiza Cortes^{a,*}, Arnold Jesfel Rejuso^b, Justine Ace Santos^b, Ariel Blanco^{b,c}^a Department of Biology and Environmental Science, College of Science, University of the Philippines Cebu, Cebu City, 6000, Philippines^b Training Center for Applied Geodesy and Photogrammetry, College of Engineering, University of the Philippines, Diliman, Quezon City, 1101, Philippines^c Department of Geodetic Engineering, College of Engineering, University of the Philippines, Diliman, Quezon City, 1101, Philippines

ARTICLE INFO

Keywords:

Urban warming
 Urban design
 Climate scenarios
 Three-dimensional simulation

ABSTRACT

Mandaue is a crucial city in Cebu island, Philippines as it links other large metropolises and is highly industrialized. The occurrence of urban heat island (UHI) in Mandaue was already confirmed by a previous study. In this paper, we aim to determine how UHI in Mandaue could be improved by mitigations including increasing vegetation, adding open spaces, employing green roofs and/or a combination thereof. ENVI-met software was utilized to simulate two study sites: M. C. Briones street and the planned urban development (PUD). To reduce computing load, M. C. Briones street was further divided into 2 subareas and PUD into 4 subareas. Results of the simulation indicate that addition of more urban spaces and trees could decrease air temperature by 0.2 °C on average while green roof could decrease air temperature by an average range of 0.2 °C–0.4 °C. When a combination of trees, grasses and green roof is used, air temperature could be decreased by an average range of 0.1 °C–0.3 °C. Despite these mitigations, thermal comfort index in Mandaue would still be greater than 26 °C which means that majority of the people would feel uncomfortable. On the other hand, addition of more urban spaces and trees could decrease surface temperature by an average range of 0.5 °C–0.8 °C while conversion of building roofs into green roofs would have no effect. When a combination of vegetation and green roof is employed, surface temperature could be decreased by an average range of 0.4 °C–1.1 °C.

1. Introduction

The concept of urban heat island or UHI, in which urban areas become warmer when compared with rural areas, was first documented in the temperate region (Oke, 1973). Decades of research has led to the fundamental understanding of UHI characteristics, mechanisms of development, and its relationship to anthropogenic heat (Aoyagi et al., 2012; Boehme et al., 2015; Taha, 1997). Using the principles of UHI formation, mitigation strategies – especially improvements in urban materials and design – have been common (Santamouris, 2013; Wonorahardjo, 2012). Specific examples include: increasing urban vegetation through parks, gardens and trees (Onishi et al., 2010; Zhou & Shepherd, 2010); adding urban ponds and rivers (Tominaga et al., 2015); using special pavements (Cortes et al., 2016; Nakayama & Hashimoto, 2011; Takahashi & Yabuta, 2009; Takebayashi & Moriyama, 2012); using high albedo materials (Dimoudi et al., 2014; D.; Li et al., 2014), etc.

* Corresponding author.

E-mail address: accortes@up.edu.ph (A. Cortes).<https://doi.org/10.1016/j.jum.2022.01.002>

Received 16 December 2020; Received in revised form 31 October 2021; Accepted 23 January 2022

Available online 10 February 2022

2226-5856/© 2022 The Authors. Published by Elsevier B.V. on behalf of Zhejiang University and Chinese Association of Urban Management. This is

an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

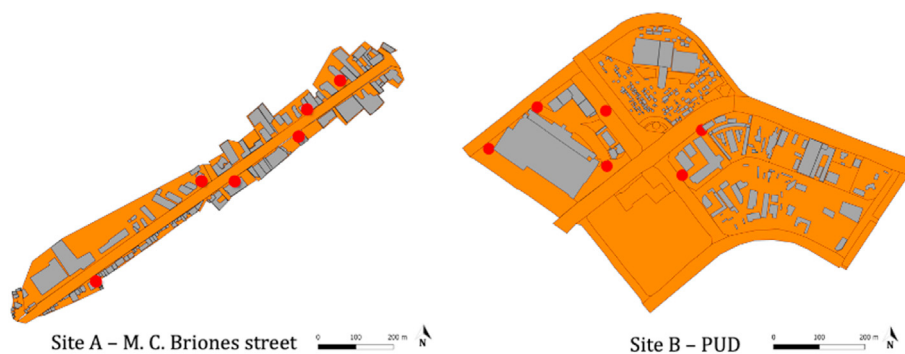


Fig. 1. Study sites in Mandaue and placement of air temperature sensors (red dots) for model validation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Mandaue is one of the most industrialized cities in Philippines and serves as a link between other big cities in Cebu island. It therefore plays a vital role in tourism, transportation, and commercial activities in the region. The development of UHI in Mandaue was already investigated by Rejuso et al. (2019) in which built-up areas that are made of urban surfaces, are densely packed and have low normalized difference vegetation index (NDVI) were found to have higher land surface temperature (LST). Considering these characteristics of UHI in Mandaue, we investigated in this paper different modifications to the current design of the built-up areas. Increasing vegetation, which consequently increases NDVI, is a common method to decrease LST due to its cooling and shadow effect (Macarof & Statescu, 2017; Mathew et al., 2017). Adding more open spaces could also mitigate UHI by creating “cold spots” and highly ventilated sections of built-up areas (Ambrosini et al., 2014; Mathew et al., 2017). The conversion of urban surfaces such building roofs into green roofs is also effective in reducing both air and surface temperatures as the solar radiation now hits the soil and plants instead of the roof surface (Mohajerani et al., 2017). Based on these facts, we decided to investigate the effects of increasing vegetation, adding open spaces, employing green roofs and/or a combination thereof to improve UHI in Mandaue. The main objective of this paper is to determine how these mitigations could affect meteorological parameters associated to UHI. Specifically, we want to predict how mitigations could influence air temperature, surface temperature, relative humidity and thermal comfort using scenario tests.

To achieve the goals of the study, ENVI-met software was used for the simulation. ENVI-met is a three-dimensional modelling tool used to investigate thermal environment including UHI (Ambrosini et al., 2014; Crank et al., 2018; Salata et al., 2016; Tsilini et al., 2015; Tsoka et al., 2018; Wang & Akbari, 2016; Wang et al., 2016). It utilizes computational fluid dynamics (CFD) to evaluate meteorological variables important in urban and rural architecture (Ambrosini et al., 2014; Salata et al., 2016). Liu et al. (2018) explained that compared with other models, mitigation by tropical plants is highly emphasized in ENVI-met model. Likewise, the metaanalysis of Tsoka et al. (2018) on UHI mitigation using cool materials and urban greening also established that nearly 90% of the published studies – which used ENVI-met as model – analysed during hot weather settings. Thus, the Philippines being in the tropical zone and having warm climate (Peel et al., 2007), ENVI-met model was deemed fit for our study. In the methods section of this paper, we also explained that the tree models in the scenario testing were chosen based on actual field observations.

2. Methods of analysis

2.1. Study area

Mandaue has twenty-seven administrative divisions called barangay and one city administered area called planned urban development 1 (hereinafter referred to as “PUD”). Fig. 1 shows the two sites within Mandaue City selected for ENVI-met analysis: site A – along M. C. Briones street between barangays Tipolo and Guizo, and site B – PUD. A section along M. C. Briones street was chosen because it represents a typical urban setup having a busy street system with different types of establishments along it. Meanwhile, PUD was chosen based on its unique characteristic of being a planned area and being excluded in the city zoning rules. In its current state, PUD still has open spaces which could change depending on property developers and city plans. In this study, the transformation of these open spaces was also simulated.

2.2. ENVI-met simulation

The Area Input File for simulation of sites A and B in ENVI-met were first created using QGIS, including geometrical data of the buildings, roads, and existing vegetation. The simulation of each study site in ENVI-met would require heavy computing because of its large size. To reduce computing load significantly, site A was divided into 2 subareas (subarea 1 and 2) while site B was divided into 4 subareas (subarea 1, 2, 3, and 4). Site A subareas 1 and 2 were 526×464 meters (m) and 529×481 m respectively with 130 buildings in total ranging from 2 to 24 m in height. Site B subareas 1, 2, 3, and 4 were 490×390 m, 560×380 m, 460×340 m and 560×310 m respectively with 249 buildings which range from 2 to 30 m in height. Simulation day was set on September 26, 2019 due its maximum heat index of 40°C in Metro Cebu for that year. Initial ENVI-met settings used in the scenario simulations are presented in Table 1.

Table 1
Input parameters used to initialize the ENVI-met simulation.

Category	Values
Start time	3:00 Local Time
Total simulation	15 h
Boundary condition	Simple Forcing
Wind speed at 10 m above ground	6 m/s
Wind direction (0:N, 90:E, 180:S, 270:W)	33.75
Roughness length	0.01
Atmospheric temperature	min = 25 °C, max = 30 °C
Relative humidity at 2 m above ground	min = 25%, max = 94%

Table 2
Settings used in scenario tests.

Element	ENVI-met ID	Description
Roads and pavements	0000ST	asphalt road
	0000 PG	concrete pavement gray
	0000 PL	concrete pavement light
	0000PD	concrete pavement dark
Green roof	01AGSS	green and sandy loam substrate
Grass	0100XX	average dense
Tree – model 1	01PLDM	palm, large trunk, dense
Tree – model 2	01SLDM	spherical, large trunk, dense
Tree – model 3	01SSDM	spherical, medium trunk, dense
Tree – model 4	01SLDL	spherical, large trunk, dense
Tree – model 5	01SMDS	spherical, medium trunk, dense

Table 3
Scenarios tested for site A – M. C. Briones street and site B – PUD in Mandaue.

Site, scenario	Code	Description
A, scenario 1	<i>siteA_{sc1}</i>	Existing layout and urban condition; 130 buildings.
A, scenario 2	<i>siteA_{sc2}</i>	Ten buildings were replaced with open spaces and 282 trees (model 3) were added along the sidewalk spaced every 10 m.
A, scenario 3	<i>siteA_{sc3}</i>	Similar to <i>siteA_{sc1}</i> 1 but building roofs were modified into green roofs.
B, scenario 1	<i>siteB_{sc1}</i>	Existing layout and urban condition; 249 buildings.
B, scenario 2	<i>siteB_{sc2}</i>	Building roofs were modified into green roofs, 39 trees (combination of tree models 1, 4, and 5) and grasses were added.

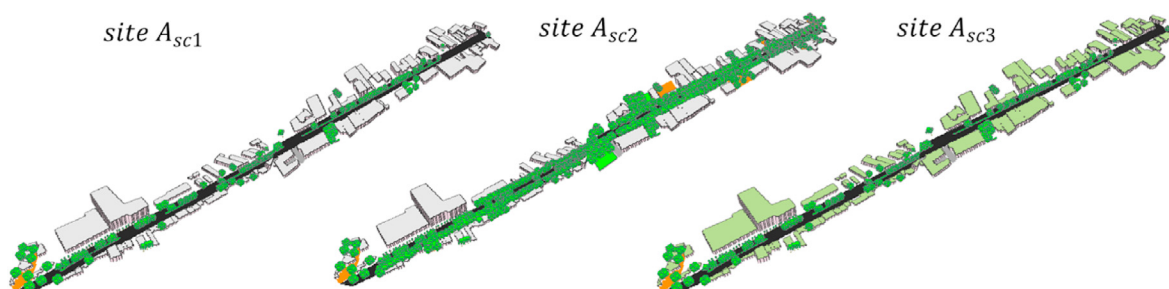


Fig. 2. Scenario simulations for site A – M. C. Briones street. Scenario 1 (*sc1*) – existing layout; scenario 2 (*sc2*) – 10 buildings were removed and 282 trees were added; scenario 3 (*sc3*) – building roofs were modified into green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Adapting the methods of Baloloy et al. (2020), boundary conditions used as ENVI-met input were derived from Dark Sky (through darksky.net) which is a weather database based on the Global Forecast System of the National Oceanic and Atmospheric Administration (Salimbeni et al., 2020) and has been widely used as weather data source (Willbur et al., 2019). In order to closely mimic the actual characteristics of each study sites, the types of urban elements including road and pavements, building height, building roof, and vegetation were set in ENVI-met based on field observations. Table 2 shows the specific urban elements chosen for the simulation and its corresponding details. Surface parameters were also set: for roads and pavements, surface albedo and emissivity were set to 0.2 and 0.9 respectively; and, for trees and green roofs, foliage albedo and foliage transmission factor were set to 0.2 and 0.3 respectively.

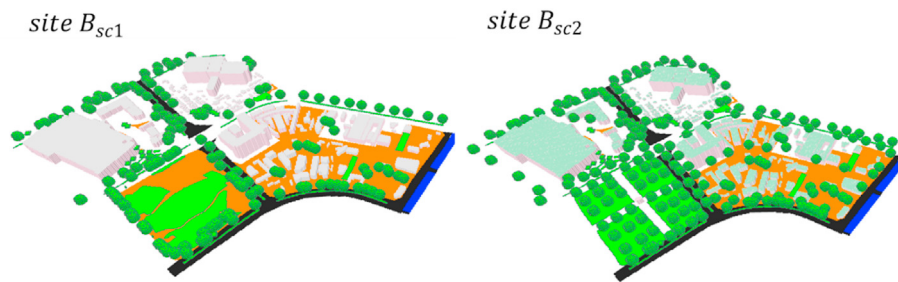


Fig. 3. Scenario simulations for site B – PUD. Scenario 1 (sc1) – existing layout; scenario 2 (sc2) – building roofs were modified into green roofs, 39 trees and grasses were added. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

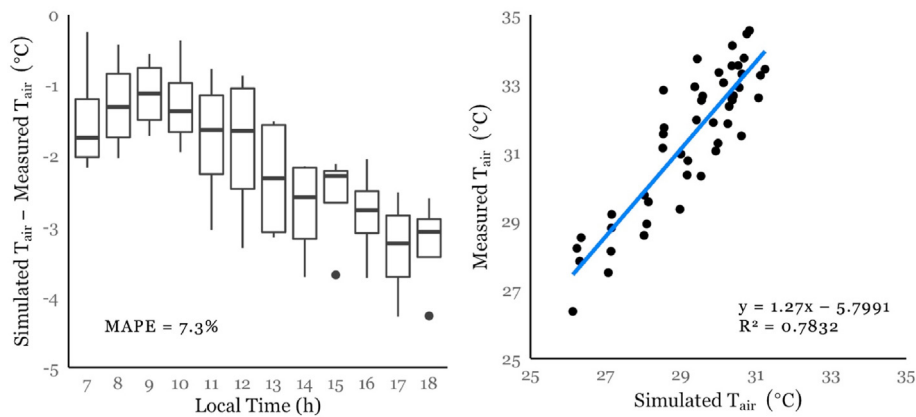


Fig. 4. Difference between air temperature measured in the field and air temperature calculated in ENVI-met.

2.3. Scenario tests

Different scenarios were evaluated to analyze the effect of various UHI mitigation strategies on UHI parameters in Mandaue. Descriptions of each scenario are presented in Table 3 and the corresponding 3D model in ENVI-met are shown in Figs. 2 and 3.

2.4. Model validation

The ENVI-met simulation was validated using measured air temperature (T_{air}) collected for seven days from February 20 to 27, 2020. A total of six HOBO MX100 sensors (± 0.5 °C accuracy) were installed in each study sites (Fig. 1) placed 1.5 m above ground and protected from direct sunlight and rain exposure. From the 7 days of field observation, measured values of T_{air} on February 25, 2020 was chosen to evaluate the model accuracy. A total of 48 data points from four sensors were used to calculate for mean absolute error (MAE) and mean absolute percentage error (MAPE).

3. Results and discussion

A box plot was created to illustrate temperature difference computed as $simulated\ T_{air} - measured\ T_{air}$. As seen in Fig. 4, the ENVI-met model underestimated T_{air} , with absolute error ranging from 0.2 to 4 °C and MAE = 2.2 °C. We attribute this discrepancy to software limitations of ENVI-met as also identified by Baloloy et al. (2020) and Cruz et al. (2021) which used the same methodology and reported similar error values. Despite this, a MAPE value of 7.3% was calculated which signifies an overall good agreement between the simulated and measured data. To further confirm model accuracy, a scatterplot of measured and simulated T_{air} was created and R-squared (R^2) was computed. The predicted trend line has high R^2 value of 0.7832 indicating strong correlation between measured and simulated T_{air} (Fig. 4). Thereby, the model was deemed appropriate for predicting outdoor thermal environment of Mandaue with adequate accuracy.

3.1. UHI mitigation in M. C. Briones street

Examination of the simulation results show that the mitigation strategies introduced in M. C. Briones street decreased air temper-

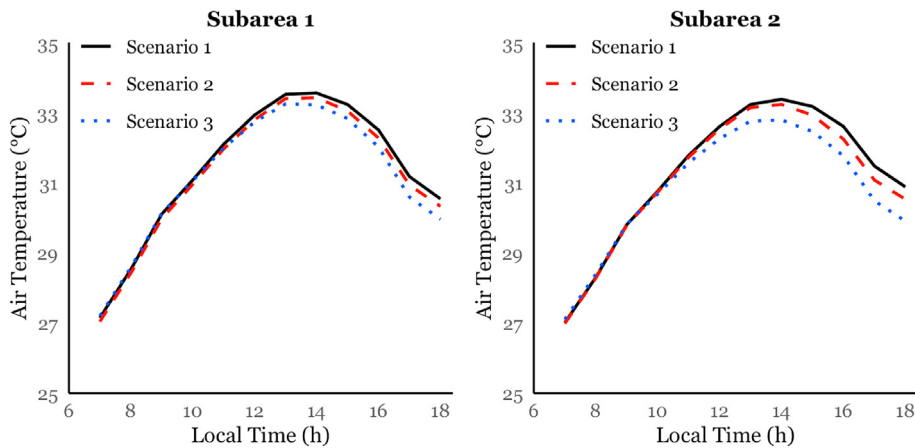


Fig. 5. Diurnal variations of air temperature in site A – M. C. Briones street under different scenarios. Scenario 1 – existing layout; scenario 2–10 buildings were removed, and 282 trees were added; scenario 3 – building roofs were modified into green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

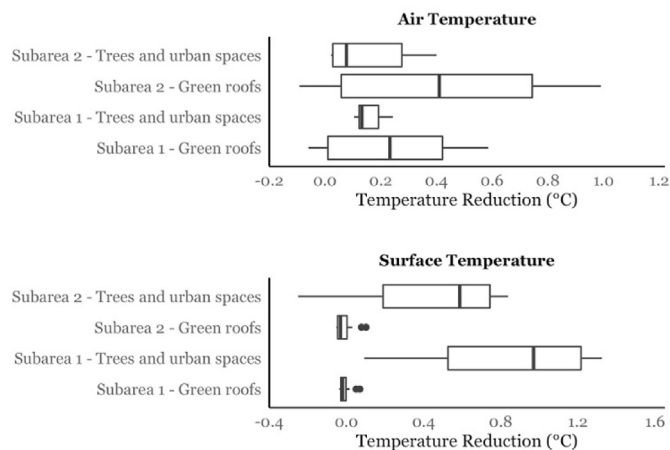


Fig. 6. Difference in temperature between scenarios tested in site A – M. C. Briones street.

ature and improved thermal comfort. Air temperature in subareas of M. C. Briones street show similar patterns of diurnal variations. Consistent in both subareas 1 and 2 across different scenarios, T_{air} is lowest early morning, peaks around 13:00–15:00 local time (LT) and eventually cools again late afternoon. Fig. 5 shows how mean T_{air} is reduced upon introduction of mitigation strategies, e.g., in subarea 1: mean $T_{air} = 31.4$ °C in $siteA_{sc1}$; mean $T_{air} = 31.2$ °C in $siteA_{sc2}$; and, mean $T_{air} = 31.1$ °C in $siteA_{sc3}$. In subarea 2: mean $T_{air} = 31.3$ °C in $siteA_{sc1}$; mean $T_{air} = 31.1$ °C in $siteA_{sc2}$; and mean $T_{air} = 30.8$ °C in $siteA_{sc3}$.

In calculating the hourly difference in T_{air} it was found that for both subareas 1 and 2, addition of more urban spaces and trees ($T_{air} site A_{sc1} - T_{air} site A_{sc2}$) could decrease T_{air} by 0.2 °C on average (Fig. 6). Meanwhile, conversion of building roofs into green roofs ($T_{air} site A_{sc1} - T_{air} site A_{sc3}$) decreased T_{air} by an average of 0.2 °C for subarea 1 and 0.4 °C for subarea 2.

Results indicate that there is only a slight difference in air temperature between the two approaches although the deployment of green roof is more effective. This is contrary to the findings of X. X. Li and Norford (2016) which showed that green vegetation could reduce air temperature greater than deploying green roof. We attribute this inconsistency to the fact that in scenario 2 of our study, we did not adapt 100% vegetation in the study site (i.e. some spaces were left open) whereas 100% green roof was adapted on all buildings in scenario 3. The buildings occupy a large percentage of the area in M. C. Briones street which is also typical in an urban environment as pointed out by Mohajerani et al. (2017). Hence, green roof covers larger surface area than the trees added which could in turn significantly reduce temperature as already proven by Herath et al. (2018). Yet, Tsoka et al. (2018) specified that the effect of green roof contributes to greater cool air advection when there is lesser distance between roof and ground surface as in the case of low-rise buildings.

Both mitigations in M. C. Briones street adopted different forms of vegetation which nonetheless reduces air temperature by increasing latent heat flux through evapotranspiration and in effect increasing humidity as well (Acero & Arrizabalaga, 2018; Lee et al., 2014; Mohajerani et al., 2017). We could not account for a large difference in evapotranspiration between scenarios 2 and 3, in fact

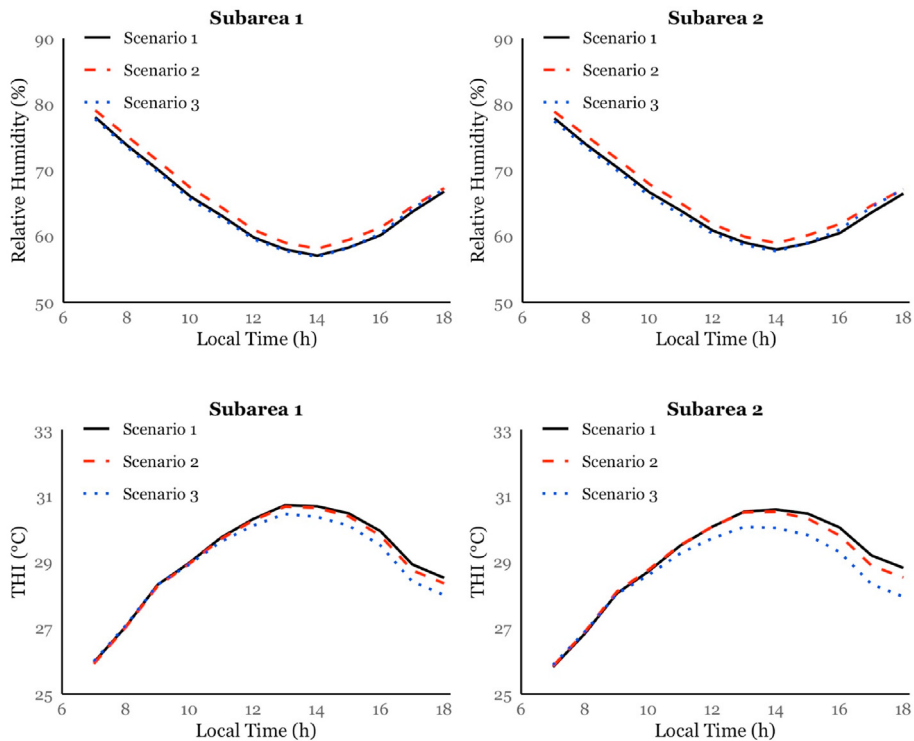


Fig. 7. Effect of UHI mitigations on relative humidity and thermal comfort index in site A – M. C. Briones street. Scenario 1 – existing layout; scenario 2–10 buildings were removed and 282 trees were added; scenario 3 – building roofs were modified into green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

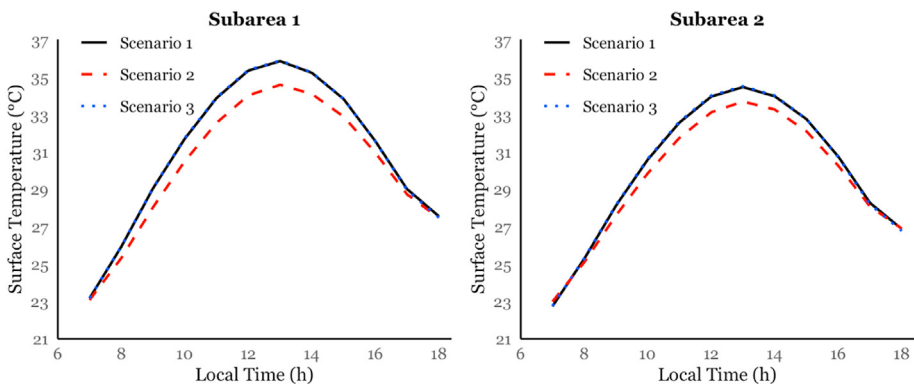


Fig. 8. Diurnal variations of surface temperature in site A – M. C. Briones street under different scenarios. Scenario 1 – existing layout; scenario 2–10 buildings were removed, and 282 trees were added; scenario 3 – building roofs were modified into green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

relative humidity only differs by 1.2% for both subareas. Fig. 7 illustrates that relative humidity in the study site is highest around 7:00–9:00 LT which could reach higher than 70% for both subareas in scenario 2 and 3. Furthermore, this study also confirms the findings of Emmanuel and Johansson (2006) which proved that relative humidity is lowest when air temperature is warmest.

Relative humidity and air temperature affect human thermal stress level; to determine the effect of these parameters on thermal comfort, we used the temperature-humidity index (THI). In the method of X. X. Li and Norford (2016), THI is calculated as $THI = 0.8t + 0.2t \times \left(\frac{RH}{100}\right)$ where t is air temperature in °C and RH is relative humidity in %. In the same study, X. X. Li and Norford (2016) explained that THI close to about 21 °C is the most ideal level where majority of the people feel comfortable while THI close to 26 °C means that majority of the people feel uncomfortable. In the simulation for subareas 1 and 2, thermal comfort for all scenarios are in the uncomfortable level i.e. $THI > 26$ °C (Fig. 7). Lowest THI range of 25.8 °C–26.0 °C is only calculated once at 7:00 LT while highest $THI \geq 30$ °C occurs during 12:00–15:00 LT. This means that the mitigations introduced were not enough to significantly minimize human

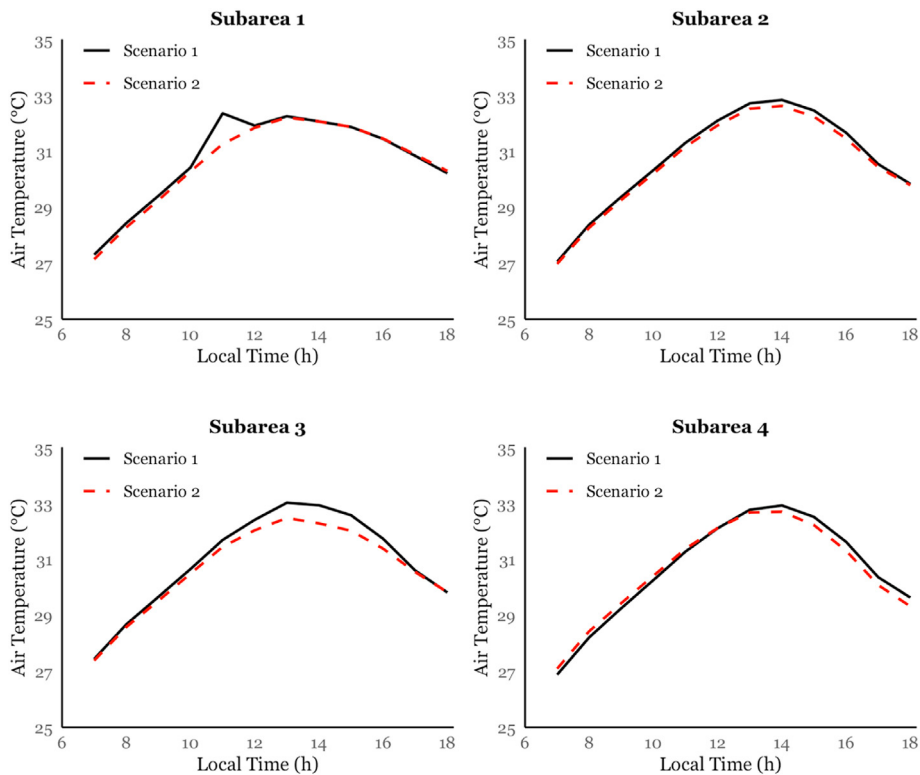


Fig. 9. Diurnal variations of air temperature in site B – PUD at different subareas under different scenarios. Scenario 1 – existing layout; scenario 2 – building roofs were modified into green roofs, 39 trees, and grasses were added. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

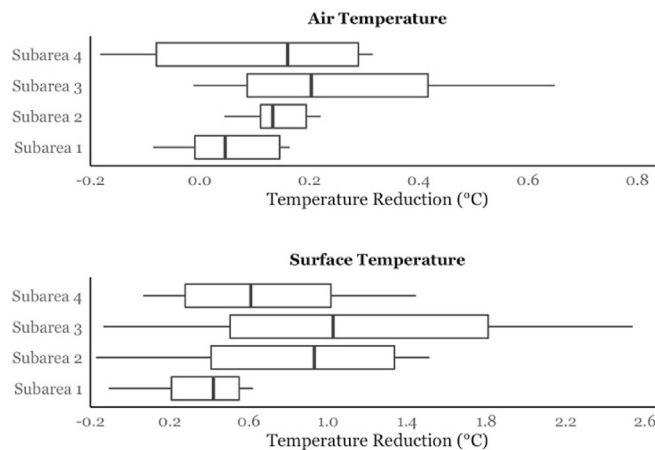


Fig. 10. Difference in temperature between scenarios tested in site B – PUD.

thermal stress.

Similar to T_{air} , surface temperature (T_{sur}) also varies diurnally where T_{sur} is lowest early morning, peaks around 12:00–15:00 LT and eventually cools again from 16:00 LT. Fig. 8 shows that mean T_{sur} is reduced upon introduction of mitigation strategy, e.g., in subarea 1: mean $T_{sur} = 31.0$ °C in site A_{sc1} ; mean $T_{sur} = 30.2$ °C in site A_{sc2} ; and, mean $T_{sur} = 31.0$ °C in site A_{sc3} . In subarea 2: mean $T_{sur} = 30.0$ °C in site A_{sc1} ; mean $T_{sur} = 29.5$ °C in site A_{sc2} ; and mean $T_{sur} = 30.0$ °C in site A_{sc3} . The difference in hourly T_{sur} was also calculated to further compare the scenarios in each subarea (Fig. 6). Addition of more urban spaces and trees (T_{sur} site $A_{sc1} - T_{sur}$ site A_{sc2}) showed that T_{sur} could be decreased by an average of 0.8 °C in subarea 1 and 0.5 °C in subarea 2 while conversion of building roofs into green roofs (T_{sur} site $A_{sc1} - T_{sur}$ site A_{sc3}) did not affect T_{sur} as temperature difference in both subareas is 0.0 °C. However, this surface temperature

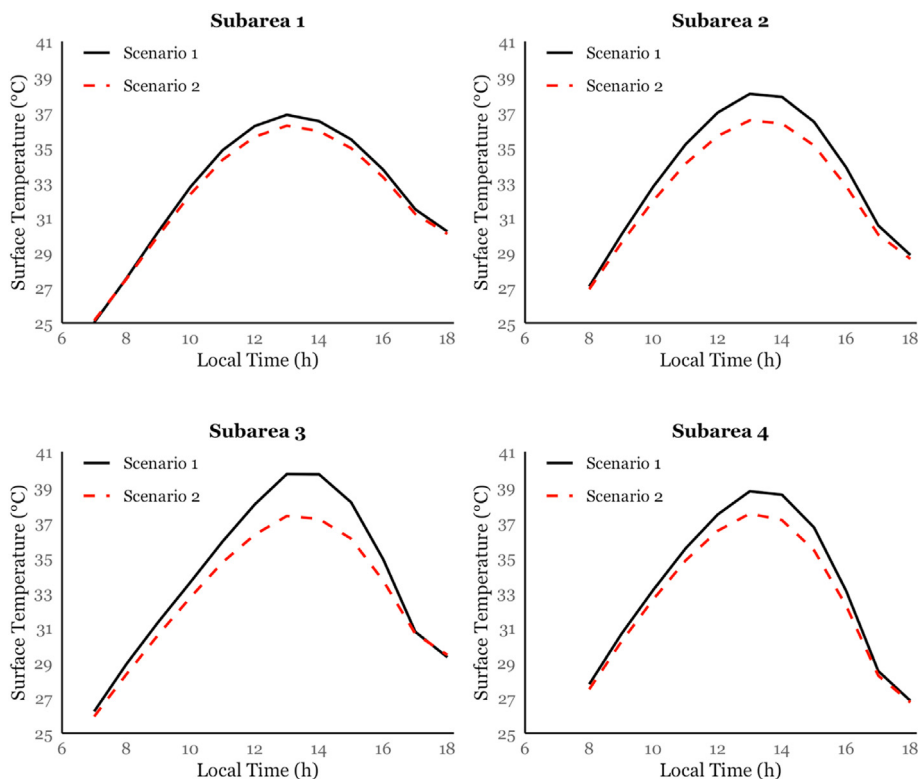


Fig. 11. Diurnal variations of surface temperature in site B – PUD at different subareas under different scenarios. Scenario 1 – existing layout; scenario 2 – building roofs were modified into green roofs, 39 trees, and grasses were added. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was calculated at 0 m while roof surfaces are at 2 m and above based on the existing buildings height. We were not able to consider roof surface temperature in this study but if it had been considered, a greater temperature reduction could be expected. The same argument was reiterated by Herath et al. (2018) in their study which ascertained that 50%–100% green roofing could lower surface temperature.

3.2. UHI mitigation in PUD

Simulation of UHI mitigation in PUD show that combined effects of green roofs and increased vegetation could decrease both air and surface temperature. Fig. 9 depicts how T_{air} changes throughout the day such that in the four subareas, T_{air} peaks during 12:00–15:00 LT and eventually cools again late afternoon. Mean T_{air} of the four subareas is consistently lower in scenario 2 than in scenario 1, with the temperature difference computed as $T_{air\ site\ B_{sc1}} - T_{air\ site\ B_{sc2}}$. UHI mitigations in $site\ B_{sc2}$ are in fact a combination of green roof, trees, and grasses which all contribute to evapotranspiration.

On average, T_{air} decreased by 0.1 °C in subarea 1, 0.1 °C in subarea 2, 0.3 °C in subarea 3 and 0.1 °C in subarea 4 (Fig. 10). We attribute the high surface temperature reduction in subarea 3 compared with other subareas in PUD due to its significant conversion from empty open space (in scenario 1) into a highly vegetated area with trees and grasses (in scenario 2). The other subareas in PUD were also added with trees in scenario 2 but the existing layout of buildings were left unchanged. Therefore, higher evapotranspiration in subarea 3 compared with other subareas is expected. Also, due to the absence of urban structures compared with other subareas, subarea 3 has the highest sky view factor. A review by Mohajerani et al. (2017) found that the sky view factor is a key parameter for the cooling effect of vegetation.

Surface temperature in PUD also follows the same diurnal pattern as air temperature, i.e., it peaks during 12:00–15:00 LT (Fig. 11). Mean T_{sur} of the four subareas is also consistently lower in scenario 2 than in scenario 1, with the temperature difference computed as $T_{sur\ site\ B_{sc1}} - T_{sur\ site\ B_{sc2}}$. On average, T_{sur} decreased by 0.4 °C in subarea 1, 0.8 °C in subarea 2, 1.1 °C in subarea 3 and 0.7 °C in subarea 4 (Fig. 10). Similar to T_{air} , we attribute the high surface temperature reduction in subarea 3 compared with other subareas in PUD due to its significant conversion into a highly vegetated area. Presence of urban greenery especially trees, are known to cool urban surfaces in various methods including: shadow effect as the leaves block incoming solar radiation (O'Malley et al., 2015; Tsoka et al., 2018; Wang et al., 2016); and, increased latent heat flux as discussed in section 3.1. In subareas 1, 2, and 4, a combination of 100% green roofing and adding few trees to empty spaces were deployed as UHI mitigation strategies in scenario 2. Hence, surface temperature in these subareas were still reduced even if roof surface temperature was not considered as in the case of scenario 3 for M. C. Briones street.

4. Conclusions

This study investigated how a change in urban design of built-up areas in Mandaue city could mitigate UHI phenomenon. Using ENVI-met, different scenarios were simulated to identify the effects of vegetation, open spaces, and green roof on parameters such as air temperature, relative humidity, thermal comfort index, and surface temperature. Addition of more urban spaces and trees could decrease air temperature by 0.2 °C on average while green roof could decrease air temperature by an average range of 0.2 °C–0.4 °C. When a combination of trees, grasses and green roof is used, air temperature could be decreased by an average range of 0.1 °C–0.3 °C. Nevertheless, the thermal comfort index in Mandaue would be greater than 26 °C despite the mitigations employed which means that majority of the people would still feel uncomfortable. On the other hand, addition of more urban spaces and trees could decrease surface temperature by an average range of 0.5 °C–0.8 °C while conversion of building roofs into green roofs would have no effect. When a combination of vegetation and green roof is employed, surface temperature could be decreased by an average range of 0.4 °C–1.1 °C.

The findings of the study imply that UHI phenomenon in Mandaue could be mitigated by several simple approaches although, in the end the choice of mitigation strategy would depend on which aspect of urban thermal environment the city wants to improve. The study also further strengthen the need to include greening in urban design as it is not only effective for cooling but also have added benefits like carbon sequestration potential and ecological service. We would therefore highly encourage the local government to adapt greening policies as well as consider UHI phenomenon in its land use plans.

For future studies, we suggest to investigate the effect of green roof on roof surface temperature and indoor air temperature.

Acknowledgements

This work is part of the Geospatial Assessment and Modelling of Urban Heat Islands in Philippine Cities Project (Project no. 4028, 2018–2019) funded by the Philippine Council for Industry, Energy, and Emerging Technology Research and Development – Department of Science and Technology. Field validation was also conducted together with the City Planning and Development Office and City Environment and Natural Resources Office of the Mandaue City Government.

References

- Acerio, J. A., & Arrizabalaga, J. (2018). Evaluating the performance of ENVI-met model in diurnal cycles for different meteorological conditions. *Theoretical and Applied Climatology*, 131(1–2), 455–469. <https://doi.org/10.1007/s00704-016-1971-y>
- Ambrosini, D., Galli, G., Mancini, B., Nardi, I., & Sfarra, S. (2014). Evaluating mitigation effects of urban heat islands in a historical small center with the ENVI-Met® climate model. *Sustainability*, 6(10), 7013–7029. <https://doi.org/10.3390/su6107013>
- Aoyagi, T., Kayaba, N., & Seino, N. (2012). Numerical simulation of the surface air temperature change caused by increases of urban area, anthropogenic heat, and building aspect ratio in the kanto-koshin area. *Journal of the Meteorological Society of Japan*, 90B, 11–31. <https://doi.org/10.2151/jmsj.2012-B02>
- Baloloy, A., Cruz, J. A., Sta Ana, R. R., Blanco, A., Lubrica, N. V., Valdez, C. J., & Bernardo, J. J. (2020). Modelling and simulation of potential future urbanization scenarios and its effect on the microclimate of lower session road, baguio city. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 5(4), 187–194. <https://doi.org/10.5194/isprs-Annals-V-4-2020-187-2020>
- Boehme, P., Berger, M., & Massier, T. (2015). Estimating the building based energy consumption as an anthropogenic contribution to urban heat islands. *Sustainable Cities and Society*, 19, 373–384. <https://doi.org/10.1016/j.scs.2015.05.006>
- Cortes, A., Shimadera, H., Matsuo, T., & Kondo, A. (2016). Evaluation of water retentive pavement as mitigation strategy for urban heat island using computational fluid dynamics. *Asian Journal of Atmospheric Environment*, 10(4), 179–189. <https://doi.org/10.5572/ajae.2016.10.4.179>
- Crank, P. J., Sailor, D. J., Ban-Weiss, G., & Taleghani, M. (2018). Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. *Urban Climate*, 26, 188–197. <https://doi.org/10.1016/j.uclim.2018.09.002>. July.
- Cruz, J. A., Blanco, A. C., Garcia, J. J., Santos, J. A., & Moscoso, A. D. (2021). Evaluation of the cooling effect of green and blue spaces on urban microclimate through numerical simulation : A case study of iloilo river esplanade , Philippines. *Sustainable Cities and Society*, 74, 103184. <https://doi.org/10.1016/j.scs.2021.103184>. July 2020.
- Dimoudi, A., Zoras, S., Kantzioura, A., Stogiannou, X., Kosmopoulos, P., & Pallas, C. (2014). Use of cool materials and other bioclimatic interventions in outdoor places in order to mitigate the urban heat island in a medium size city in Greece. *Sustainable Cities and Society*, 13, 89–96. <https://doi.org/10.1016/j.scs.2014.04.003>
- Emmanuel, R., & Johansson, E. (2006). Influence of urban morphology and sea breeze on hot humid microclimate: The case of Colombo, Sri Lanka. *Climate Research*, 30(3), 189–200. <https://doi.org/10.3354/cr030189>
- Herath, H. M. P. I. K., Halwatura, R. U., & Jayasinghe, G. Y. (2018). Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. *Urban Forestry and Urban Greening*, 29, 212–222. <https://doi.org/10.1016/j.ufug.2017.11.013>. November 2017.
- Lee, J. S., Kim, J. T., & Lee, M. G. (2014). Mitigation of urban heat island effect and greenroofs. *Indoor and Built Environment*, 23(1), 62–69. <https://doi.org/10.1177/1420326X12474483>
- Li, D., Bou-Zeid, E., & Oppenheimer, M. (2014). The effectiveness of cool and green roofs as urban heat island mitigation strategies. *Environmental Research Letters*, 9(5), Article 055002. <https://doi.org/10.1088/1748-9326/9/5/055002>
- Li, X. X., & Norford, L. K. (2016). Evaluation of cool roof and vegetations in mitigating urban heat island in a tropical city, Singapore. *Urban Climate*, 16, 59–74. <https://doi.org/10.1016/j.uclim.2015.12.002>
- Liu, Z., Zheng, S., & Zhao, L. (2018). Evaluation of the ENVI-met vegetation model of four common tree species in a subtropical hot-humid area. *Atmosphere*, 9(5). <https://doi.org/10.3390/ATMOS9050198>
- Macarof, P., & Statescu, F. (2017). Comparison of NDBI and NDVI as indicators of surface urban heat island effect in landsat 8 imagery: A case study of iasi. *Present Environment and Sustainable Development*, 11(2), 141–150. <https://doi.org/10.1515/pesd-2017-0032>
- Mathew, A., Khandelwal, S., & Kaul, N. (2017). Investigating spatial and seasonal variations of urban heat island effect over Jaipur city and its relationship with vegetation, urbanization and elevation parameters. *Sustainable Cities and Society*, 35, 157–177. <https://doi.org/10.1016/j.scs.2017.07.013>. July.
- Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, 197, 522–538. <https://doi.org/10.1016/j.jenvman.2017.03.095>
- Nakayama, T., & Hashimoto, S. (2011). Analysis of the ability of water resources to reduce the urban heat island in the Tokyo megalopolis. *Environmental Pollution*, 159(8–9), 2164–2173. <https://doi.org/10.1016/j.envpol.2010.11.016>
- Oke, T. (1973). *City size and the urban heat island* (Vol. 7, pp. 769–779). Atmospheric Environment Pergamon Press. [https://doi.org/10.1016/0004-6981\(73\)90140-6](https://doi.org/10.1016/0004-6981(73)90140-6)
- O'Malley, C., Piroozfar, P., Farr, E. R. P., & Pomponi, F. (2015). Urban heat island (UHI) mitigating strategies: A case-based comparative analysis. *Sustainable Cities and Society*, 19, 222–235. <https://doi.org/10.1016/j.scs.2015.05.009>

- Onishi, A., Cao, X., Ito, T., Shi, F., & Imura, H. (2010). Evaluating the potential for urban heat-island mitigation by greening parking lots. *Urban Forestry and Urban Greening*, 9(4), 323–332. <https://doi.org/10.1016/j.ufug.2010.06.002>
- Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5), 1633–1644. <https://doi.org/10.5194/hess-11-1633-2007>
- Rejuso, A. M., Cortes, A. C., Blanco, A. C., Cruz, C. A., & Bataan, J. B. (2019). Spatio-temporal analysis of urban heat island in Mandaue City, Philippines. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(4/W19), 361–367. <https://doi.org/10.5194/isprs-archives-XLII-4-W19-361-2019>
- Salata, F., Golasi, I., de Lieto Vollaro, R., & de Lieto Vollaro, A. (2016). Urban microclimate and outdoor thermal comfort. A proper procedure to fit ENVI-met simulation outputs to experimental data. *Sustainable Cities and Society*, 26, 318–343. <https://doi.org/10.1016/j.scs.2016.07.005>
- Salimbeni, A., Porru, M., Massidda, L., & Damiano, A. (2020). A forecasting-based control algorithm for improving energy management in high concentrator photovoltaic power plant integrated with energy storage systems. *Energies*, 13(18), 1–20. <https://doi.org/10.3390/en13184697>
- Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island - a review of the actual developments. *Renewable and Sustainable Energy Reviews*, 26, 224–240. <https://doi.org/10.1016/j.rser.2013.05.047>
- Taha, H. (1997). Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings*, 25(2), 99–103. [https://doi.org/10.1016/S0378-7788\(96\)00999-1](https://doi.org/10.1016/S0378-7788(96)00999-1)
- Takahashi, K., & Yabuta, K. (2009). Road temperature mitigation effect of “road cool,” a water-retentive material using blast furnace slag. *JFE Technical Report*, 13(13), 58–62.
- Takebayashi, H., & Moriyama, M. (2012). Study on surface heat budget of various pavements for urban heat island mitigation. *Advances in Materials Science and Engineering*, 2012. <https://doi.org/10.1155/2012/523051>. Article ID 523051 2012.
- Tominaga, Y., Sato, Y., & Sadohara, S. (2015). CFD simulations of the effect of evaporative cooling from water bodies in a micro-scale urban environment: Validation and application studies. *Sustainable Cities and Society*, 19, 259–270. <https://doi.org/10.1016/j.scs.2015.03.011>
- Tsilini, V., Papanтониου, S., Kolokotsa, D. D., & Maria, E. A. (2015). Urban gardens as a solution to energy poverty and urban heat island. *Sustainable Cities and Society*, 14(1), 323–333. <https://doi.org/10.1016/j.scs.2014.08.006>
- Tsoka, S., Tsikaloudaki, A., & Theodosiou, T. (2018). Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications—A review. *Sustainable Cities and Society*, 43, 55–76. <https://doi.org/10.1016/j.scs.2018.08.009>
- Wang, Y., & Akbari, H. (2016). Analysis of urban heat island phenomenon and mitigation solutions evaluation for Montreal. *Sustainable Cities and Society*, 26, 438–446. <https://doi.org/10.1016/j.scs.2016.04.015>
- Wang, Y., Berardi, U., & Akbari, H. (2016). Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. *Energy and Buildings*, 114, 2–19. <https://doi.org/10.1016/j.enbuild.2015.06.046>
- Willbur, J., McCaghey, M., Kabbage, M., & Smith, D. L. (2019). An overview of the Sclerotinia sclerotiorum pathosystem in soybean: Impact, fungal biology, and current management strategies. *Tropical Plant Pathology*, 44(1), 3–11. <https://doi.org/10.1007/s40858-018-0250-0>
- Wonorahardjo, S. (2012). New concepts in districts planning, based on heat island investigation. *Procedia - Social and Behavioral Sciences*, 36, 235–242. <https://doi.org/10.1016/j.sbspro.2012.03.026>. June 2011.
- Zhou, Y., & Shepherd, J. M. (2010). Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards*, 52(3), 639–668. <https://doi.org/10.1007/s11069-009-9406-z>